

Medium-modified Jets and Initial State Fluctuations as Sources of Charge Correlations Measured at RHIC

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We investigate the contribution of medium-modified jets and initial state fluctuations to the asymmetry in charged particle production with respect to the reaction plane. This asymmetry has been suggested as a compelling signature of the Chiral Magnetic Effect in QCD and make a study of "conventional" scenarios for the creation of such charged particle multiplicity fluctuations a timely endeavor. The different pathlength combinations of jets through the medium in non-central heavy ion collisions result in finite correlations of like and different charged particles emitted in the different hemispheres. Our calculation is based on combining jet events from YaJEM (Yet another Jet Energy Loss Model) and a bulk medium evolution. It is found that the jet production probabilities are too small to observe this effect. The influence of initial state fluctuations on this observable is explored using an event-by-event (3+1)d hybrid approach that is based on UrQMD (Ultra-relativistic Quantum Molecular Dynamics) with an ideal hydrodynamic evolution. In this calculation momentum conservation and elliptic flow are explicitly taken into account. The asymmetries in the initial state are translated to a final state momentum asymmetry by the hydrodynamic flow profile. Dependent on the size of the initial state fluctuations the resulting charged particle asymmetries are in qualitative agreement with the preliminary STAR results. The multi-particle correlation as proposed by the PHENIX collaboration can in principle be used to disentangle the different contributions, however is in practice substantially affected by the procedure to subtract trivial resonance decay contributions.

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I. INTRODUCTION

Ultra-relativistic heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) are thought to have created a high temperature and pressure state of QCD matter termed the Quark-Gluon-Plasma (QGP) [1–5]: Two major discoveries stand out: (1) the emission of hadrons with a transverse momentum p_T of several GeV/c or more is strongly suppressed (jet-quenching), implying the presence of matter with a very large color opacity, and (2) the anisotropic ("elliptic") flow in non-central collisions is near the ideal hydrodynamic limit, requiring an early onset of the period during which the expansion is governed by fluid dynamics (earlier than 1 fm/c after the initial impact) as well as nearly ideal fluid properties with a viscosity-to-entropy density ratio $\eta/s \ll 1$. The matter created at RHIC has been thus called the strongly interacting Quark-Gluon Plasma (sQGP) [6] and quantifying its properties in terms of its transport coefficients is one of the major tasks of the current experimental and theoretical research program.

One should note that QCD matter created in relativistic heavy-ion collisions may possess a very rich set of features, reflecting the fundamental symmetries (and violations thereof) of QCD, well beyond the above noted characteristics of large opacity and near-ideal fluidity. Among the more intriguing features which are currently being searched for is the presence of the Chiral Magnetic Effect (CME) [7–10]: as was pointed out in [7], non-central heavy-ion collisions create a coherent magnetic field that

may convert topological charge fluctuations in the QCD vacuum into global electric charge fluctuations with respect to the reaction plane. While the magnitude of the charge fluctuations which can be attributed to the CME is still a matter of ongoing debate [9, 10], the STAR collaboration has recently reported that charge fluctuations with respect to the reaction plane have indeed been seen [11].

In order to confirm the discovery of the CME in relativistic heavy-ion collisions, one first needs to verify that experimental measurements cannot be understood in terms of "conventional", well-established, phenomena observed at RHIC. It has recently been pointed out that correlations from charge and momentum conservation at freeze-out overlaid with elliptic flow may very well be able to describe the observed phenomena [12, 13]. In addition, the experimental observable suggested to measure the CME has been argued to be predominantly sensitive to other effects [14, 15].

In this paper we focus on estimating various conventional physics mechanisms that lead to charge particle number asymmetry within a realistic model, namely medium-modified jets as well as initial state fluctuations, combined with well-known bulk physics such as momentum conservation, resonance decays and elliptic flow. In Section II the different observables that have been proposed are introduced. These observables are surely sensitive to fluctuations of multiplicity (and charge) if these fluctuations are correlated with the reaction plane. Both of the two scenarios that we are studying here, in-medium jets (in Section III) and initial state granularity (in Sec-

tion IV) give a particular mechanism to generate multiplicity fluctuations correlated in a peculiar way with the reaction plane. Only once all possible contributions to the observed charged particle fluctuations with respect to the reaction plane are accounted for, can we quantify the possible contribution of the CME to the measurements.

II. DEFINITION OF OBSERVABLES

The standard observable used to look for the CME is the angular correlation coefficient

$$\gamma_{\alpha,\beta} = \frac{\sum_{i \in \alpha, j \in \beta} \cos(\phi_i + \phi_j)}{M_\alpha M_\beta} \quad (1)$$

where α and β represent positive and negative charges, ϕ measures the angle with respect to the reaction plane orientation and M are the measured multiplicities. As argued in [12, 13, 15], this observable is (contrary to initial expectations) dominated by a strong in-plane like-sign correlation which has no obvious relation with charge separation as proposed as signal of the CME.

In the present study we consider two other newly developed observables to quantify the correlations of charged particles with the reaction plane for which a computation using a detailed framework is feasible with a reasonable amount of CPU time. In addition, these observables seem to have a clearer relation to out-of-plane charge separation.

A. Charge Asymmetry Observable

The first observable we focus on for measuring the event-by-event charged particle asymmetry has been developed by the Purdue group within the STAR collaboration [16]. The measurement is based on counting charged particles that are emitted into different hemispheres with respect to the reaction plane. The different hemispheres are defined as follows: 'Up=U' means $p_y > 0$, 'Down=D' refers to $p_y < 0$, 'Left=L' stands for $p_x < 0$ and 'Right=R' for $p_x > 0$. The UD-direction reflects the out-of-plane direction whereas the LR-direction represents the in-plane direction.

The charged particle asymmetry coefficients are defined in the following way

$$(A_{UD}^+)^2 = \frac{(N_U^+ - N_D^+)^2}{(N_U^+ + N_D^+)^2} \quad (2)$$

$$(A_{UD}^-)^2 = \frac{(N_U^- - N_D^-)^2}{(N_U^- + N_D^-)^2} \quad (3)$$

$$A_{UD}^{+/-} = \frac{(N_U^+ - N_D^+)(N_U^- - N_D^-)}{(N_U^+ + N_D^+)(N_U^- + N_D^-)} \quad (4)$$

and correspondingly for the LR-direction where N^+ and N^- are the numbers of positively and negatively charged particles in one event.

The opposite charge correlation ($A_{UD}^{+/-}$ and $A_{LR}^{+/-}$) are positive, if the particles tend to be aligned and negative for a charge separation scenario. Without any correlation this observable would be consistent with zero. The $(A^+)^2$ and $(A^-)^2$ are a measure of the overall charged particle fluctuation. The preliminary STAR results seem to be positive (on the order of $1 \cdot 10^{-3}$) in the out-of-plane as well as the in-plane direction for mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV. The main difference of this observable compared to the original angular correlation measurement [11, 18] is that each particle contributes with the same weight independent of its position in the respective hemisphere.

B. Multi-Particle Correlation

The PHENIX collaboration has recently proposed a different observable that is sensitive to a charge separation with respect to the reaction plane as it is predicted from the chiral magnetic effect [17]. This multi-particle correlation coefficient relies on an event-by-event measurement technique and is defined as follows

$$C_p = \frac{dN/d(\Delta S_{ch})}{dN/d(\Delta S_{all})} \quad (5)$$

where

$$\Delta S = \frac{1}{P} \sum_{i=1}^P \sin(\phi_i^+) - \frac{1}{M} \sum_{i=1}^M \sin(\phi_i^-) \quad (6)$$

Here, the first sum runs over all positively charged particles in one event whereas M is the number of negatively charged particles in one event and ϕ is the azimuthal angle in the transverse plane in momentum space. ΔS_{all} is the analogous quantity where the i th particle is randomly chosen from the event. This observable is a multi-particle correlation that has to be measured event by event. The ratio of the charge sensitive distribution to the one for all charged particles is flat at 1, if there is no charge specific correlation (e.g. elliptic flow). A concave shape indicates charge separation out of plane (e.g. the presence of the CME) and a convex shape arises, if positively and negatively charged particles are preferably emitted in the same direction (e.g. resonance decays).

III. MEDIUM-MODIFIED JETS

A. Overview

The idea of jets as a mechanism to generate asymmetries in the charged multiplicity distribution is based on the notion that in-medium energy loss from a leading parton is dominated by induced gluon radiation [19, 20], giving rise to additional multiplicity production. Moreover, this mechanism is predominantly active out of plane: While radiative energy loss asymptotically has an L^2 dependence in a constant medium, the actual scaling of lost energy and produced multiplicity in a real situation is complicated and has no simple functional shape for a number of reasons, among them the spacetime evolution of the bulk medium which reduces the density as a function of space and time and the re-interaction of radiated gluons with the medium, leading to a cascade of induced radiation till finite energy corrections become manifest [21]. However, the multiplicity of medium-induced hadron production is a monotonously rising function of both pathlength and medium density.

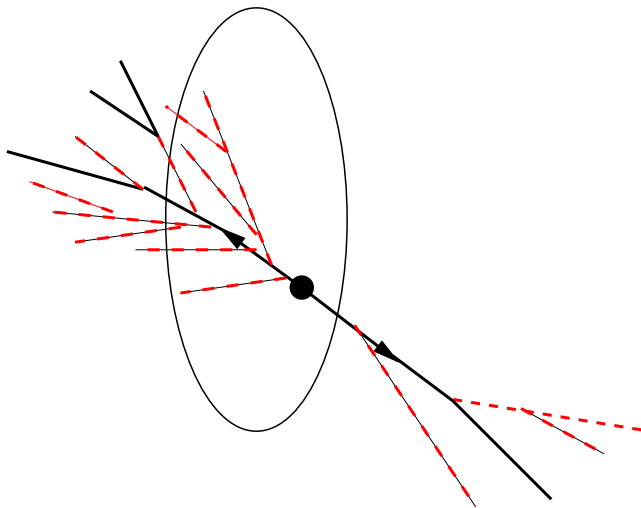


FIG. 1: Sketch of the hadron multiplicity asymmetry induced by medium-modified showers: for a shower evolving in the medium, induced gluon radiation leads to larger multiplicity production.

The basic idea how medium modified jets may generate an asymmetry in the charged hadron multiplicity correlated out of the reaction plane is shown in Fig. 1. Let us start with a random initial hard vertex position in the transverse plane: if the vertex position is such that one jet is close to the surface and escapes unmodified whereas the other jet propagates a long distance through the medium, the average multiplicity of charged hadrons for both jets is expected to be very different. Furthermore, this effect can be estimated to be stronger in the up-down direction than in the left-right direction, simply because the maximum variation in pathlength is larger for out of plane emission than for in-plane emission.

Note that jets lead to an asymmetry in charged hadron production event by event even without a medium modification, simply because the fragmentation of a hard parton to a hadron jet is a probabilistic process, and also because jets in hadronic collisions may be due to a pQCD subprocess like $qg \rightarrow qg$ in which the fragmentation of the gluon in the out state is much softer from the fragmentation of the quark. However, in the presence of a medium, the medium-induced radiation is expected to dominate multiplicity production, and the vacuum case has no mechanism to account for a correlation with the reaction plane. In the following, we use the in-medium shower evolution code YaJEM (Yet another Jet Energy-loss Model) in the RAD (radiative energy loss) scenario to estimate the jet-induced event by event charged hadron multiplicity asymmetry.

B. Model Description

YaJEM is a Monte Carlo code to simulate the medium-modified evolution of a parton shower. It is based on the PYSHOW algorithm [22, 23] for shower evolution in vacuum, to which it reduces in the absence of a medium. A detailed description of the model is given in [24, 25], here we just summarize the essential physics underlying the model.

In YaJEM, the evolution from the initial parton to a final state parton shower is modelled as a series of branching processes $a \rightarrow b+c$ where a is called the parent parton and b and c are referred to as daughters. In QCD, the allowed branching processes are $q \rightarrow qg$, $g \rightarrow gg$ and $g \rightarrow q\bar{q}$. The kinematics of a branching is described in terms of the virtuality scale Q^2 and of the energy fraction z , where the energy of daughter b is given by $E_b = zE_a$ and of the daughter c by $E_c = (1-z)E_a$. It is convenient to introduce $t = \ln Q^2/\Lambda_{QCD}^2$ where Λ_{QCD} is the scale parameter of QCD. t takes a role similar to a time in the evolution equations, as it describes the evolution from some high initial virtuality Q_0 (t_0) to a lower virtuality Q_m (t_m) at which the next branching occurs. In terms of the two variables, the differential probability dP_a for a parton a to branch is

$$dP_a = \sum_{b,c} \frac{\alpha_s}{2\pi} P_{a \rightarrow bc}(z) dt dz \quad (7)$$

where the splitting kernels $P_{a \rightarrow bc}(z)$ read

$$P_{q \rightarrow qg}(z) = 4/3 \frac{1+z^2}{1-z} \quad (8)$$

$$P_{g \rightarrow gg}(z) = 3 \frac{(1-z(1-z))^2}{z(1-z)} \quad (9)$$

$$P_{g \rightarrow q\bar{q}}(z) = N_F/2(z^2 + (1-z)^2). \quad (10)$$

We do not consider electromagnetic branchings. N_F counts the number of active quark flavours for given virtuality. The resulting system of equations describing the

branching processes in vacuum is solved numerically using MC techniques utilizing the PYSHOW code [22, 23].

In order to make the link from momentum space where the shower evolution takes place to position space where the medium perturbations evolve, we assume that the average formation time of a shower parton with virtuality Q is developed on the timescale $1/Q$, i.e. the average lifetime of a virtual parton with virtuality Q_b coming from a parent parton with virtuality Q_a is in the rest frame of the original hard collision (the local rest frame of the medium may be different by a flow boost as the medium may not be static) given by

$$\langle\tau_b\rangle = \frac{E_b}{Q_b^2} - \frac{E_b}{Q_a^2}. \quad (11)$$

We assume that the actual formation time can then be obtained from a probability distribution

$$P(\tau_b) = \exp\left[-\frac{\tau_b}{\langle\tau_b\rangle}\right] \quad (12)$$

which we sample to determine the actual formation time of the fluctuation in each branching.

The medium modification in the RAD scenario appears as a change of parton virtuality ΔQ_a^2 dependent on a medium parameter \hat{q} where

$$\Delta Q_a^2 = \int_{\tau_a^0}^{\tau_a^0 + \tau_a} d\zeta \hat{q}(\zeta). \quad (13)$$

Here, the time τ_a is given by Eq. (12), the time τ_a^0 is known in the simulation as the endpoint of the previous branching process and the integration $d\zeta$ is along the eikonal trajectory of the shower-initiating parton. If the parton is a gluon, the virtuality transfer from the medium is increased by the ratio of their Casimir color factors, $3/4/3 = 2.25$. \hat{q} is a function of medium energy density ϵ with the relation chosen such that the single pion suppression observed in 200 AGeV central Au-Au collisions at RHIC is described [25].

As a result of the medium-induced change in virtuality, additional gluon radiation occurs which after hadronization leads to an increased multiplicity in the shower.

C. Results

In order to estimate the event by event charged hadron asymmetry, we embed back-to-back jet pairs of three different energies (10, 20 and 40 GeV per jet) into a 3+1 d hydrodynamical simulation [26] on a random position sampled from the binary collision profile. The jet pair then gets a random orientation with respect to the reaction plane. We then propagate both jets through the medium and evaluate Eq. (13) to determine the medium modification. After hadronizing the jets, we count the charged hadron content in the four different quadrants

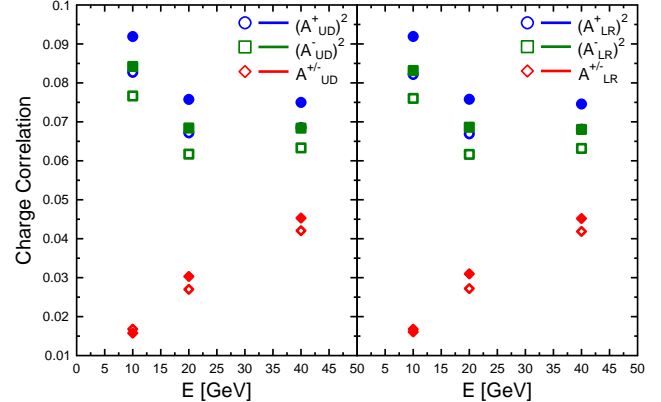


FIG. 2: (Color online) Contribution of medium-modified jets to the charged particle asymmetry coefficients in the out-of-plane (left) and in-plane (right) direction for three different initial parton energies (10, 20 and 40 GeV) for Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV. Open symbols depict central collisions ($b = 2.4$ fm) while filled symbols represent mid-central collisions ($b = 7.5$ fm).

and compute the asymmetry coefficients $(A^+)^2$, $(A^-)^2$ and A^{+-} . The results are shown in Fig. 2.

The result indicates that jets are in principle capable of creating substantial charge correlations. In this scenario the charge correlation arises because of an asymmetry in the particle production. The correlation shown in Fig. 2 shows that in a developing shower the balancing charges are preferably emitted in the same hemisphere, so positively and negatively charged particles tend to align. However, somewhat surprisingly, no pronounced difference between up-down and left-right is visible. This can be traced back to a number of reasons. First, Eq. (13) evaluated in an expanding medium leads to small modifications at late times, i.e. for long paths, as \hat{q} becomes very small when the energy density of the system is low. This means that in an expanding medium, partons do not actually probe the full length difference between in-plane and out-of-plane emission, but rather probe pathlength difference during the time period when modifications are significant only, i.e. the first ~ 3 -5 fm/c. Given this 'filter', the differences between in-plane and out-of-plane emission are considerably smaller than estimated naively based on geometry. Furthermore, especially for low p_T hadron production, the angular distribution of hadrons around the jet axis is wide [25, 27]. Note that this can happen even if the jet shape itself is rather narrow, as the jet shape traces the flow of momentum and not multiplicity. The fact that there can be significant multiplicity created also in the down hemisphere even from a shower initiating parton travelling into the up hemisphere further weakens the difference between in-plane and out-of-plane emission.

So far, we have investigated the charge correlation coefficients created by a single jet only. This is not a very realistic situation: First, high momentum jets of e.g. 40 GeV are very rare events, so even if they create sizeable asymmetries in charged multiplicity, such events may not have much weight in an average over many events. Second, for low momentum jets, one cannot assume that only a single jet per event contributes. However, it is immediately clear that embedding multiple jets in an event weakens the asymmetry significantly. When we account for these effects by mixing jets with the probability of a jet with given energy being in the event determined from a LO pQCD calculation into a UrQMD background [28, 29], the picture changes considerably: In Fig. 3 the contribution of jets appears as an insignificant correction to the background result.

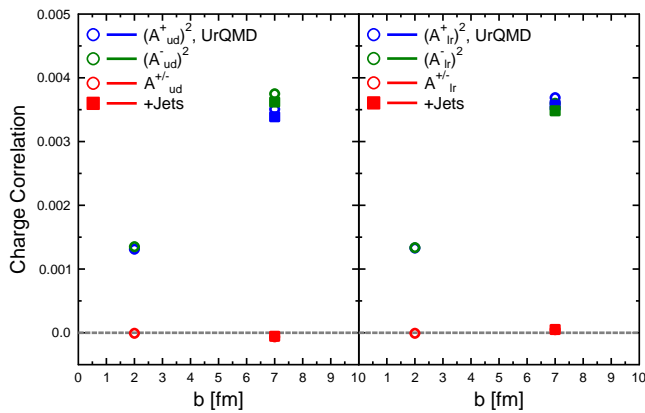


FIG. 3: (Color online) Calculation of the charged particle asymmetry coefficients in the out-of-plane (left) and in-plane (right) direction for two different centralities for Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV. The open circles depict the results from the hadronic transport approach (UrQMD) that serves as a background for the full calculation including medium-modified jets that is represented by full squares.

In hindsight, this could have been anticipated: While truly hard jets are too rare to influence the result, low p_T jets (below 5 GeV) tend to be created frequently, but the presence of multiple jets in an event tends to cancel their effect. Clearly, a bulk mechanism creating charge asymmetries is more efficient than a rare probe.

Note also that it is apparent from Fig. 3 that UrQMD background results show that a pure hadronic transport approach is not capable of translating initial state fluctuations to the final state distributions effectively enough to lead to a significant signal as the $A^{+/-}$ coefficients are on the order of $1 \cdot 10^{-6}$.

In Fig. 4 the calculation of the multi-particle correlation coefficient is shown. Medium-modified jets, embedded in a UrQMD background lead to a convex shape of the ratio of the distributions in ΔS . The result for jets

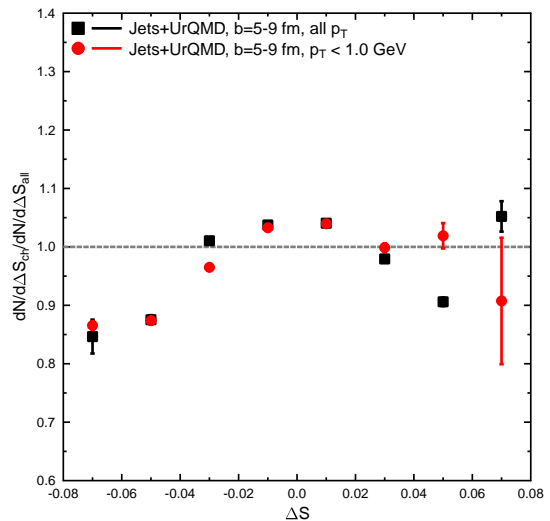


FIG. 4: (Color online) Calculation of the multi-particle correlation coefficient in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV. The full squares depict the results from the full calculation including medium-modified jets to the hadronic transport approach (UrQMD) background event, whereas the full circles show the result only for particles with $p_T < 1$ GeV.

alone leads to the same shape as the combined events. But again, the probability for jet production is very low and therefore the results resemble very much the UrQMD results that are shown in Fig. 9. Furthermore, the influence of a $p_T < 1$ GeV cut has been explored, since the preliminary measurements have been made in a limited p_T range and the chiral magnetic effect is mostly expected in the bulk low transverse momentum region. The low p_T result and the result for all charged particles are the same within error bars and especially the shape does not change. Since the distribution of the charge sensitive averaged sine differences has a higher peak around zero and lower flanks than the distribution that is not charge specific this result indicates that particles with opposite charges are preferably emitted in the same direction than in different directions. The underlying physics mechanism in both cases is correlated particle production from 'clusters' - in one case jets, in the other decaying resonances.

IV. INITIAL STATE FLUCTUATIONS

A. Overview

In the second part of this article the charged particle asymmetry that arises from well-known bulk medium effects is investigated. The basic idea is that energy den-

sity clusters produced by the initial binary scatterings in heavy ion reactions might lead to asymmetry correlations in the particle production in different hemispheres. Due to the development of radial flow during the medium evolution the initial coordinate space granularity is translated to a resulting momentum space anisotropy. These clusters are expected to enhance the multiplicity in a specific hemisphere which results in alignment of the charged particle production instead of separation. In this picture, resonance decays might explicitly introduce a charge correlation of the outgoing particles, if e.g. a ρ meson decays into $\pi^+ + \pi^-$ and there is enough collective flow, both of the pions will preferably have a momentum in a similar direction.

S. Pratt recently estimated the effects of elliptic flow, momentum and charge conservation on the observable charged particle correlation measurement [13]. Our approach follows a similar spirit but the effect of initial state fluctuations is emphasized in addition. This kind of event-by-event fluctuations has been found to be crucial also for other two-particle correlation measurements (the 'ridge') at the highest RHIC energies [30].

B. Model Description

The charged particle asymmetry that is generated by clusters in the initial energy density distribution is quantified by using a hybrid approach based on the UrQMD hadronic transport approach including a (3+1)-dimensional one fluid ideal hydrodynamic evolution [31, 32] for the hot and dense stage of the reaction while the early non-equilibrium stage and the final decoupling is treated in the hadronic cascade [33, 34] [40].

The event-by-event-setup that is naturally employed in this approach is crucial for the observation of charged particle asymmetries. For Au+Au collisions at the highest RHIC energy the starting time for the hydrodynamic evolution has been chosen to be $t_{\text{start}} = 0.3 - 1.8$ fm depending on the amount of fluctuations to fit the final pion multiplicity at midrapidity, since this is crucial for the present study and allows us to investigate the effect of the initial state granularity on the charge correlations. How the change in the starting time affects other bulk observables like spectra and elliptic flow will be discussed in a further publication [35]. Only the matter around midrapidity ($|y| < 2$) is considered to be locally thermalized and takes part in the ideal hydrodynamic evolution. The more dilute spectator/corona regions are treated in the hadronic cascade approach. To map the point particles from the UrQMD initial state to energy, momentum and net baryon density distributions three-dimensional Gaussian distributions are used that represent one particle each [36].

$$\epsilon_{\text{cf}}(x, y, z) = N \exp - \frac{(x - x_p)^2 + (y - y_p)^2 + (\gamma_z(z - z_p))^2}{2\sigma_{\text{Gauss}}^2}, \quad (14)$$

where $N = (\frac{1}{2\pi})^{\frac{3}{2}} \frac{\gamma_z}{\sigma_{\text{Gauss}}^3} E_{\text{cf}}$ provides the proper normalisation, ϵ_{cf} and E_{cf} are the energy density and total energy of the particle in the computational frame, while (x_p, y_p, z_p) is the position vector of the particle. Summing over all single particle distribution functions leads to distributions of energy-, momentum- and baryon number-densities in each cell.

The transition from the hydrodynamic evolution to the transport approach when the matter is diluted in the late stage is treated as a gradual transition on an approximated iso-eigentime hyper-surface (see [37, 38] for details). The final rescatterings and resonance decays are taken into account in the hadronic cascade.

To investigate the effect of different initial state granularities the width of the Gaussian distribution (14) is varied from $\sigma_{\text{Gauss}} = 0.8 - 2.0$ fm. Please note that this is still an event-by-event setup and in this respect different from averaging over many fluctuating initial conditions as has been done in [39]. In a hydrodynamic calculation starting from smooth initial profiles the correlation observable would be zero, since there are no event-by-event fluctuations included.

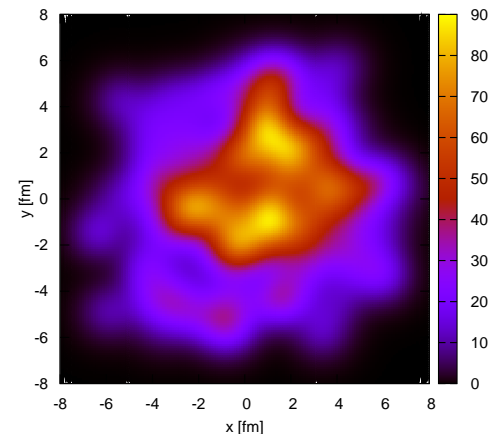


FIG. 5: (Color online) Energy density distribution in the transverse plane for a central ($b=0$ fm) Au+Au collision at $\sqrt{s_{\text{NN}}} = 200.4$ GeV with $\sigma_{\text{Gauss}} = 0.8$ fm and $t_{\text{start}} = 0.3$ fm.

Fig. 5-7 show the initial energy density distribution as it is obtained from UrQMD for three different values of the Gaussian width $\sigma_{\text{Gauss}} = 0.8, 1.0$ and 2.0 fm. A smaller width leads to entropy production during the ideal hydrodynamic evolution indicating that the solution of the differential equation is not stable anymore. Therefore, the highest fluctuations are generated with the smallest width of 0.8 fm, while for larger widths the initial fluctuations are more and more smeared out. Smaller characteristic sizes could be physically motivated by a color flux tube picture where structures in the transverse plane on the order of 0.3 fm would be expected. Our

parameter choices stay in a regime where the implementation is technically stable and the characteristic sizes correspond to typical sizes of a proton.

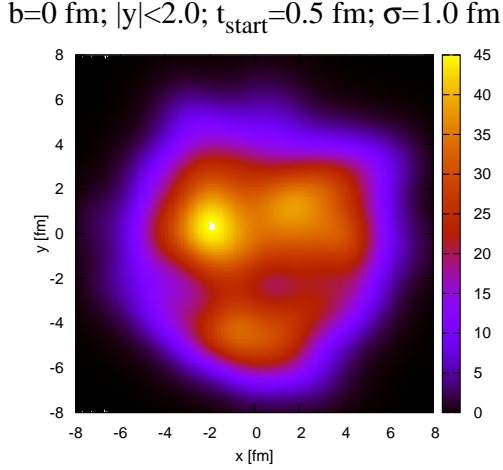


FIG. 6: (Color online) Energy density distribution in the transverse plane for a central ($b=0$ fm) Au+Au collision at $\sqrt{s_{NN}} = 200A$ GeV with $\sigma_{Gauss} = 1.0$ fm and $t_{start} = 0.5$ fm.

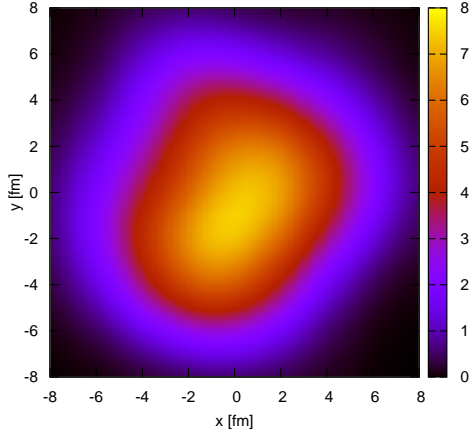


FIG. 7: (Color online) Energy density distribution in the transverse plane for a central ($b=0$ fm) Au+Au collision at $\sqrt{s_{NN}} = 200A$ GeV with $\sigma_{Gauss} = 2.0$ fm and $t_{start} = 1.8$ fm.

C. Results

The hybrid approach provides the opportunity to study the influence of initial state fluctuations that can be varied in size without adjusting any other parameter

on event-by-event particle production in different hemispheres. Initial state clusters and a coordinate space-momentum space correlation due to radial flow leads to observable differences in the charged particle production in different parts of the system (see Fig. 8). The UD and LR charged particle asymmetry coefficients have been calculated for four different initial granularities in the hybrid approach. The open symbols depict the results for central ($b < 3.4$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV and the filled symbols represent mid-central ($b = 5 - 9$ fm) Au+Au collisions. The overall fluctuations of charged particles are larger in non-central collisions than in central collisions because the overall multiplicity is smaller. The opposite charge asymmetry is positive and similar in the out-of-plane and the in-plane direction. This confirms the expectations that in this scenario the particles tend to align independent of their charge. Within our limited statistics, the absolute value of the difference between UD and LR can be constrained to be smaller than $1 \cdot 10^{-3}$.

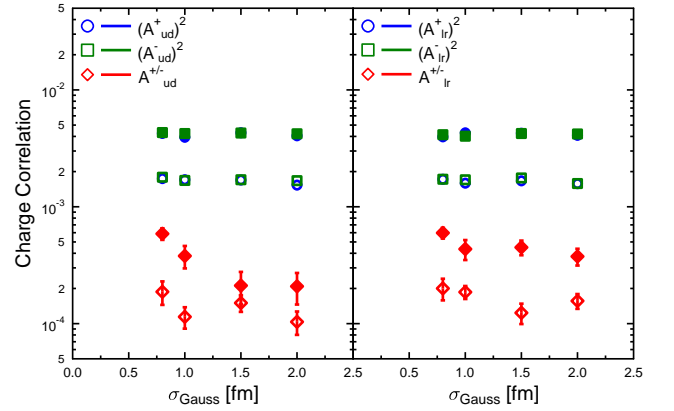


FIG. 8: (Color online) Calculation of the charged particle asymmetry coefficients in the out-of-plane (left) and in-plane (right) direction for four different values of σ_{Gauss} . The open symbols depict the results for central ($b < 3.4$ fm) Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV and the filled symbols represent mid-central ($b = 5 - 9$ fm) Au+Au collisions.

Higher granularity in the initial state leads to higher opposite charge asymmetry coefficients that are on the order of the preliminary STAR data [16]. This physics mechanism will contribute to the background of a potential measurement of the chiral magnetic effect and needs to be taken into account, before trying to look for a potentially much smaller signal. On the other hand, the comparison of hybrid calculation with different initial state granularities to event-by-event correlation and fluctuation measurements might be helpful to constrain the structure of the initial state of relativistic heavy ion reactions.

Fig. 9 shows the result for the multi-particle correla-

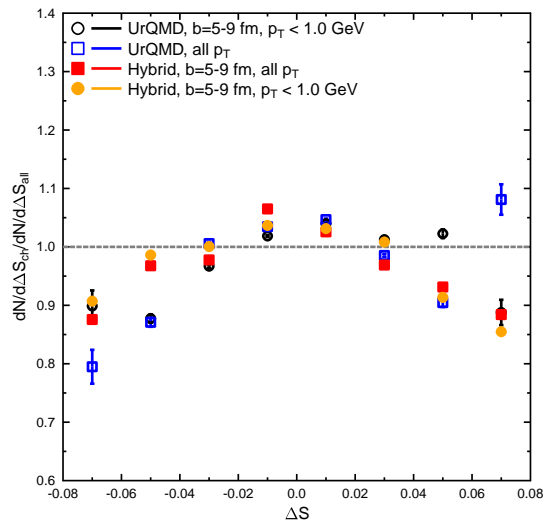


FIG. 9: (Color online) Calculation of the multi-particle correlation coefficient in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200A$ GeV. The open symbols depict the results from the hadronic transport approach (UrQMD) (circles indicate an additional $p_T < 1$ GeV cut) and the filled symbols represent calculations within the hybrid approach.

tion coefficient that has been defined in Section II B from the UrQMD hadronic transport approach (open symbols) and the hybrid approach (filled symbols). It has been checked that the results for this observable do not depend on the choice of σ_{Gauss} . The low transverse momentum region shows the same behaviour as without p_T cut. If one reduces the number of particles by acceptance (or other) cuts, the distribution broadens, however does not change qualitatively in shape. Again the correlations induced by these approaches lead to a convex shape and can be attributed to resonance decays whereas a charge separation scenario as expected from the chiral magnetic effect leads to a concave shape in this observable. The initial state fluctuations have to be considered as a non-trivial source of correlations of the particles emitted in a heavy ion reaction.

It is likely that any measurement of the observable is dominated by resonance decay effects which are known to be present in nature. In order to observe a different mechanism (like the CME) at work, this distribution has to be subtracted. In order to get an idea of the sensitivity of the results to the subtraction, we have tried

to isolate the effect of initial state fluctuations by subtracting the UrQMD distributions in ΔS from the hybrid model distributions. It turns out that the procedure is very sensitive to the subtraction - we were able to observe even qualitative differences in shape which could potentially mock up the CME signal.

V. SUMMARY AND CONCLUSIONS

We have investigated charge asymmetry and multi-particle correlations with the reaction plane generated in relativistic heavy-ion collisions at RHIC within a realistic transport approach containing a full medium evolution and medium-modified jets. While jets are in principle capable of generating the aforementioned multi-particle correlations, we were able to rule them out as a significant contributor to such correlations due to the low jet production rate. However, we find that initial state fluctuations can generate values for the charge asymmetry coefficients on the same order of magnitude as seen by experiment. Our results were obtained within a hybrid transport approach, based on an event-by-event hydrodynamic evolution, with fluctuating initial conditions and microscopic hadronic afterburner for the realistic treatment of hadronic final state effects, including resonance decays. The precision of our calculation was not sufficient to quantify the difference between in-plane and out-of-plane, due to the very large computational effort involved. However, the coefficients themselves show no sign of charge separation. The multi-particle correlation measurement proposed by the PHENIX collaboration appears to be potentially the most suitable of the studied observables for differentiating a CME from other mechanisms. However, due to the need of subtracting known background effects like resonance decays, it is currently unclear whether the predicted concave shape as a signal for the CME can be robustly established.

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